NASA Technical Memorandum 4131

Flight Evaluation of a Pneumatic System for Unsteady Pressure Measurements Using Conventional Sensors

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CONTENTS

SUMMARY

A flight experiment was conducted to evaluate a pressure measurement system which uses pneumatic tubing and remotely located electronically scanned pressure transducer modules for in-flight unsteady aerodynamic studies. A parametric study of tubing length and diameter on the attenuation and lag of the measured signals was conducted.

The hardware was found to operate satisfactorily at rates of up to 500 samples/sec per port in flight. The signal attenuation and lag due to tubing were shown to increase with tubing length, decrease with tubing diameter, and increase with altitude over the ranges tested. Measurable signal levels were obtained for even the longest tubing length tested, 4 ft, at frequencies up to 100 Hz.

This instrumentation system approach provides a practical means of conducting detailed unsteady pressure surveys in flight.

INTRODUCTION

As efficient aircraft design increasingly relies on the prediction of unsteady aerodynamics, the need for high-frequency pressure measurements is becoming more critical. In-flight measurement techniques for frequencies in excess of 20 Hz are needed to validate unsteady aerodynamic analysis codes used for the prediction of flutter and aeroservoelasticity. Regions of separated flow, vortex impingement, and phenomena such as vortex and shock-induced oscillations can be identified with detailed unsteady pressure surveys. In-flight unsteady pressure measurements also may prove useful to support flutter clearance testing. Despite these potential applications, few detailed in-flight unsteady pressure surveys have been made.

A flight experiment was devised to test whether a pneumatic unsteady pressure measurement system with conventional sensors could be used effectively for research flight testing. The specific objectives of the study were as follows:

1. To demonstrate the operation of a scanning pressure transducer module and data system at rates up to 500 samples/sec per port in a flight environment;

2. To perform a limited parametric study of tubing geometry (diameter and length);

3. To determine the level of high-frequency information that can be obtained through pneumatic tubing;

4. To determine whether transfer functions can be determined for later use in correcting remotely sensed data for pneumatic effects.

The background, experimental setup, flight test techniques, and data analysis methods used to address these objectives are described. A discussion of the results is included.

NOMENCLATURE

ESP   electronically scanned pressure
ID   inside diameter
OWRA   oblique wing research airplane
PCM   pulse code modulation
PSD   power spectral density

BACKGROUND

Conventional unsteady pressure measurements rely on pressure transducers which are installed flush to the aircraft surface or connected to an orifice on the surface by a short pneumatic tube (approximately 1 in.). An example of this type of instrumentation is described in Hess and others (1987). In many flight applications, access to wing cavities for transducer installation or maintenance is difficult if not impossible. Sometimes redundant transducers are installed at each measurement location so that replacement of failed transducers is not necessary. The wide range of temperatures experienced in flight generally requires that the transducers be either temperature controlled (to prevent the output from drifting out of range) or have a filter to remove the steady-state value. If filtered, an additional measurement system would be required to provide steady pressure data. Flush-mounted transducers are also exposed to a variety of undesired high-frequency input (for example, from engine noise) and therefore require antialias filtering. Electronic filtering introduces spectral distortion (magnitude and phase characteristics) that must be accounted for in the data reduction process. All of these problems add to the system complexity and cost. For these reasons, in-flight unsteady pressure surveys generally have been limited in scope.

Steady pressure surveys obtained in flight typically avoid these problems through the use of flush surface orifices, pneumatic tubing, and remotely located transducers. This approach allows the use of an electronically scanned pressure (ESP) module consisting of multiple transducers that are scanned and multiplexed onto a common data channel. The ESP can use a single temperature control system to prevent range drift of all transducers in the module. These features have made it possible to obtain detailed steady pressure surveys in flight at a reasonable cost.

Whenever tubing and remote transducers are used for unsteady data, the pneumatic effects (magnitude and phase distortion of the actual surface pressure fluctuations) must be accounted for. The majority of analysis to determine these pneumatic effects, such as Lamb (1957), is related to high-volume pneumatic systems and low-frequency data requirements (for applications such as air data measurements). Some studies (Tijdeman, 1977; Bergh and Tijdeman, 1965) have concentrated on systems designed for use at frequencies up to 100 Hz. Results from these studies have been used to successfully predict the pneumatic effects of tubing in correlation with laboratory studies of oscillating pressures at the orifice (Chapin, 1983). These analytical methods, however, do not accurately account for the effect of flows over the surface of an orifice which produce energy in the higher harmonic frequencies. In a wind tunnel application of pneumatic tubing for unsteady pressures (Seidel and others, 1987), the pneumatic effects were found to be small and measurable. In this case, however, the tubing length was only 18 in., too short for most flight test applications.

The authors show that for some in-flight applications, pneumatically sensed systems can provide suitable high-frequency pressure data. This approach will allow more extensive unsteady pressure surveys at a reasonable cost. One proposed application of this system was the F-8 oblique wing research airplane (OWRA) (Gregory, 1985) in which in-flight steady and unsteady pressures were to be measured over a wide range of wing sweeps and flight conditions. A system of about 400 flush orifices connected to 13 ESP modules and only 40 surface-mounted transducers was envisioned for this project. Obtaining this quantity of data through independent steady and unsteady measurement systems would not have been practical because of the cost and installation complexity.

EXPERIMENTAL HARDWARE AND INSTALLATION

The experimental hardware was installed in the right wing of an F-15 research airplane (fig. 1(a)). An access panel on the leading edge was used to install various flush orifices on the wing surface and to stow other system hardware (fig. 1(b)). A schematic of the experimental system is shown in figures 2(a) and 2(b).

The orifice installation hardware was fabricated from approximately 1 in. of metal tubing with the desired inside diameter (nominally 0.02, 0.04, or 0.06 in.). A washer was soldered around the tubing approximately 0.25 in. from one end, and the unit was inserted from the inside of the wing skin through holes of appropriate diameter and epoxied

in place. The protruding tubing then was filed flush with the wing surface. Specific lengths of flexible tubing with similar inside diameter as the metal orifice were used to connect the orifice to an ESP module. The measured inside diameters (IDs) of the orifices and flexible tubing are given in table 1. For the remainder of this paper, the nominal values are used.

The ESP module (fig. 3) consists of 32 silicon-diaphragm, piezoresistive-pressure transducers. Data from the ESP module were recorded at a rate of 250 samples/sec per port for the initial flights. The rate was later increased to 500 samples/sec. The diameter of each ESP differential diaphragm is 0.040 in. and is attached to a 0.59-in. metal tube also of 0.040-in. diameter. The module multiplexes the individual port measurements, the output is sent to a 10-bit pulse code modulation (PCM) system, and recorded on onboard tape. The ESP module does not provide for signal conditioning prior to multiplexing. The ESP module transducers were ranged from -5 to $+5$ psi. A heater blanket was installed to maintain a constant temperature on the ESP module.

The reference side of the ESP module was connected to an ambient pressure reservoir that was vented to the interior wing cavity. The reservoir allowed the reference pressure (backside of the ESP differential transducer) to adjust to changes in altitude without high-frequency pressure oscillations. One port of the ESP module was connected to this reservoir. Since this port was not exposed to the external flow, it was used to determine the inherent noise level in the measurement system and was referred to as the system "health" channel.

The data presented in this paper were obtained from two groups of orifices on the upper surface of the wing along the 10-percent chord line. These orifice groups are separated by about 12 in. and can be seen in figure 1(b).

The first group consisted of two 0.06-in. ID orifices 0.5 in. apart. One of these orifices was connected to the ESP module with 6 in. of tubing throughout the flight tests. The other orifice was connected with tubing lengths of either 2 or 4 ft. These are designated group I orifices.

The second group consisted of three orifices with IDs of 0.02, 0.04, and 0.06 in. These were located along a 2-in. segment of the 10-percent chord line. Tubing lengths of either 2 or 4 ft were used with these three orifices. These orifices are referred to as group II orifices.

Freestream air data parameters were measured with conventional nose-boom sensors. These data were acquired through an independent onboard system which telemetered the PCM encoded channels to a ground station.

FLIGHT MANEUVERS

Specific flight maneuvers were conducted to generate high-frequency pressure fluctuations over the experimental orifices. These maneuvers consisted of constant altitude, constant Mach number windup g turns. The maximum g level (about 2.5 g) was held for approximately 10 sec.

The experimental system collected data for over 14 flights; the majority of the flight time was devoted to unrelated experiments. During postflight analysis of certain engine performance test manuevers, high-frequency, high-amplitude fluctuations were noted in the pressure time histories. As a result, these maneuvers, consisting of high-power setting constant altitude turns, were also used to evaluate the unsteady pressure measurement system.

DATA ANALYSIS

Time history pressure data from the onboard tape were replayed onto strip chart recorders. These strip charts were analyzed visually to identify time frames (approximately 30 to 60 sec in duration) that included substantial high-frequency excitation. Flight conditions during these time frames were determined from the air data instrumentation system.

Time history pressure data from each port were input to a digital spectral analyzer. Power spectral density (PSD) distributions were computed, averaged (in blocks of 1024 samples) over the maneuver time frame, and plotted. The results for a given manuever were overlayed and normalized. The PSD distributions were computed over a range of 0 to 100 Hz with a resolution of 0.25 Hz. The frequency response of the piezoresistive-type transducers was assumed to be linear in this range.

The spectral analyzer was also used to generate transfer functions between the two group I orifices (using the 6-in. line length orifice as reference). Transfer functions between the group II orifices were also obtained (using the 0.06-in. diameter orifice as reference).

RESULTS AND DISCUSSION

Qualitative Analysis

Time histories from a typical windup turn maneuver are shown in figure 4(a) (this data is displayed at a lower rate than the recorded signals). The two group I orifices have the same low-frequency characteristics. The time histories from the group II orifices are consistent among themselves but substantially different from the group I data. This may be a result of the physical separation (about 12 in.) of the two orifice groups in the flow field.

As the aircraft reaches an angle of attack of about 8°, an increase in the amplitude of high-frequency pressure fluctuations can be seen in the short (6 in.) tubing configuration. The other group I port, with 2 ft tubing length, also exhibits an increase in high-frequency fluctuations although the amplitude is considerably lower. The high-frequency pressure fluctuations in the group II orifice data (all with 2 ft tubing) show increasing attenuation with decreasing orifice diameter.

The aerodynamic mechanism that produces these unsteady pressure fluctuations was not determined owing to the limited scope of the experiment. High-frequency content in the data generally occurred during flight at high angles of attack, indicating that leading edge vortex flows may be present. It is clear that local velocity over the port may not be proportional to the freestream velocity. As a result, no correlation of results with airspeed was attempted.

The level of activity on the system "health" channel did not change during the maneuvers, indicating that the pressure fluctuations on the other channels is indeed a result of external flow conditions and not a result of system noise induced by other sources. The level of activity on this channel never varied significantly throughout the flight test program.

Time histories of the group II orifice data, which include rapid pressure jumps (step changes), are shown in figure 4(b). This step change of about 0.4 psi occurs in less than 0.01 sec for the 0.06-in. diameter orifice. As orifice diameter decreases, the time required to achieve this amplitude increases.

Power Spectral Density

Two combinations of power spectral density are shown in this report. First, in figure 5, the PSD for the short (6 in.) tubing orifice is compared with the PSD distributions from the two longer tubing configurations with the same diameter of 0.06 in. Second, in figure 6, PSD levels from the group II orifices, which had varying diameter but constant line length, are compared. In both cases the PSD for the health channel is shown as the threshold (or noise) level.

In figure 5(a), the PSD distributions for the two longer tubing configurations have similar characteristics and are nearly superimposed. The 2 ft and short (6 in.) tubing results are equal at very low frequencies, but the ratio of PSD level for the long to the short tubing drops to about 0.3 (−10 dB) at higher frequencies up to 100 Hz. However, the

4

threshold level is at least 30 dB lower than the 2 ft tubing data at all frequencies, indicating that a significant amount of energy can be observed with this tubing length at frequencies up to 100 Hz.

In the comparison of 4-ft tubing length with the short 6-in. tubing (fig. 5(b)), the PSD levels are again equivalent at low frequencies, but the 4-ft tubing data drops to the threshold level by 30 Hz.

In figure 6, the comparison of three different orifice diameters with 2-ft tubing length indicates that signal-to-noise ratio increases steadily with increasing diameter. The signal from the 0.02-in. ID orifice reduces to the threshold level at frequencies of about 60 Hz.

The PSD levels were analyzed to determine the frequency at which the signal-to-noise ratio dropped to 10 dB. This frequency is shown in figure 7 for varying tubing geometries and pressure altitudes. However, this information was obtained from maneuvers in which the amplitude of unsteady pressure fluctuations at the surface orifices may have varied slightly. Data in this figure indicate that large signal-to-noise ratios for a wide range of frequencies were obtained in this particular experiment, but without relating the measured signals to the actual surface pressures, limited conclusions can be drawn regarding the usefulness of a pneumatic sensing system.

Since no true surface measurements were available, the short 6-in. tubing configuration was used as a pseudo surface measurement. The ratio of PSD level for 2- and 4-ft tubing lengths to the PSD level of the 6-in. tubing length is shown in figure 8. All data in this figure are for 0.06-in. diameter, group I, orifices. The attenuation generally increases with tubing length and altitude. At 40,000 ft, the 4-ft tubing length signal has dropped to the threshold level at high frequencies.

Transfer Function Analysis

Transfer functions were obtained for the long tubing length group I orifice referenced to the short 6-in. tubing length orifice (fig. 9). Because of their physical proximity, the surface flow field of the two orifices is expected to be equivalent, and, therefore, the transfer functions were taken to represent the effect of tubing length. In figure 9(a), reasonable phase and magnitude trends can be identified throughout the frequency range, although the scatter in the data increases above 25 Hz. The 4-ft tubing data (fig. 9(b)) shows similar trends, but larger phase angles. Transfer functions such as these can be used to relate the pneumatically sensed data to actual surface pressure fluctuations.

The transfer functions for the 0.04- and 0.02-in. orifices referenced to the corresponding 0.06 orifice are shown in figure 10. These three orifices were in group II (in close physical proximity) and had equal tubing lengths. These comparisons were made to assess the effects of orifice diameter.

The transfer functions (fig. 10) for tubing lengths of 2 ft imply that corrections for the pneumatic line effects should be possible at frequencies as high as 50 Hz. The results of figure 10 show that decreasing orifice diameter from 0.06 to 0.04 or 0.02 in. increases phase angle and amplitude loss. In retrospect, it would have been interesting to include large diameter orifices in this study, since the optimal diameter for system response may be greater than 0.06 in. Data are also shown for 20,000-, 30,000-, and 40,000-ft altitude maneuvers. The phase angle and reduction in magnitude tend to increase with increasing altitude. These trends are consistent with both the qualitative assessment and PSD analysis already discussed.

CONCLUDING REMARKS

The results from this flight experiment have shown that a considerable amount of high-frequency pressure information can be obtained from an ESP-based system that uses pneumatic tubing of moderate line lengths.

The ESP unit operated satisfactorily at high sample rates (250 and 500 samples/sec) throughout the testing. The noise in the system was a well-defined constant low level throughout the tests.

Transfer functions were obtained between pressure signals from various pneumatic tubing geometries. The attenuation and phase shifts were shown to increase with increasing tubing length, decreasing orifice diameter, and increasing altitude. Results were obtained which can be used to predict the high-frequency performance of future systems for tubing lengths up to 4 ft and diameters in the range of 0.02 to 0.06 in.

Measurable signal levels at frequencies up to 100 Hz were demonstrated for 2-ft tubing lengths at all altitudes tested and for 4-ft tubing lengths at altitudes up to 30,000 ft. Since the performance of the system improved with increasing diameter throughout the range tested, it is possible that using larger diameter orifices (greater than 0.06 in.) might allow the use of tubing lengths longer than 4 ft.

Transfer functions of magnitude and phase angle were generated for all maneuvers analyzed. The quality of the data indicates that corrections for the pneumatically sensed pressures could be made at frequencies at least as high as 25 Hz.

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Gregory, Tom, "Oblique Wing Ready for Research Aircraft," *Aerospace America*, vol. 23, no. 6, June 1985, p. 78.

Hess, Robert W., David A. Seidel, William B. Igoe, and Pierce L. Lawing, *Highlights of Unsteady Pressure Tests on a 14 Percent Supercritical Airfoil at High Reynolds Number, Transonic Condition*, NASA TM-89080, 1987.

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Seidel, David A., Maynard C. Sandford, and Clinton V. Eckstrom, "Measured Unsteady Transonic Aerodynamic Characteristics of an Elastic Supercritical Wing," *AIAA Journal of Aircraft*, vol. 24, no. 4, Apr., 1987, pp. 225–230.

Tijdeman, H., *Investigations of the Transonic Flow Around Oscillating Airfoils*, NLR-TR-77090-U, National Aerospace Lab, Amsterdam, Netherlands, 1977. (Available from DTIC as AD B027 633.)
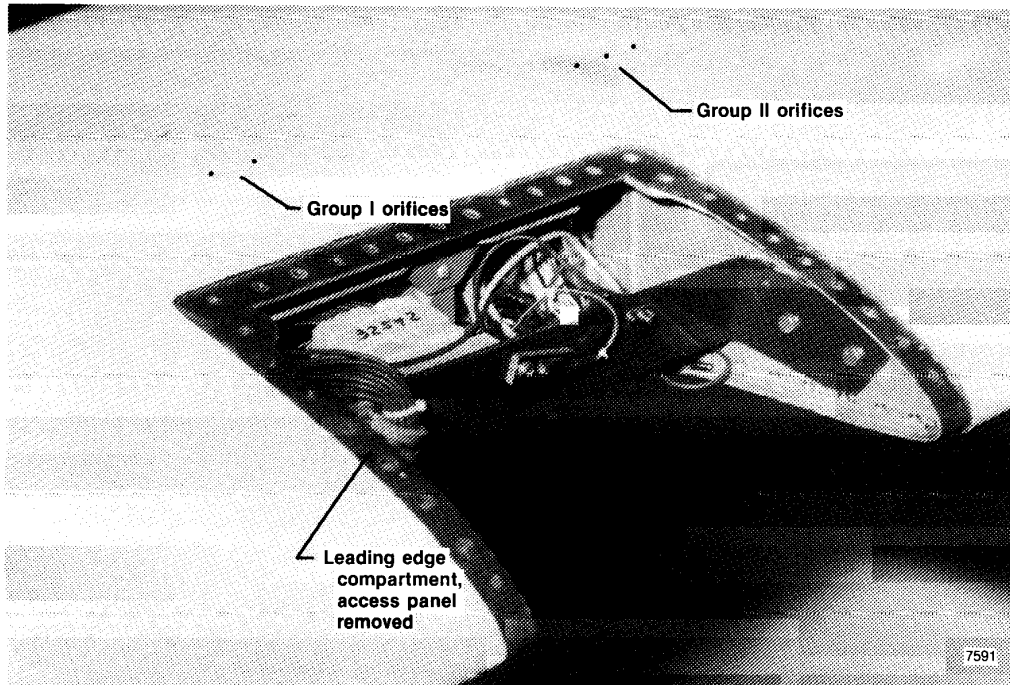
TABLE 1. ORIFICE AND TUBING INSIDE DIAMETERS

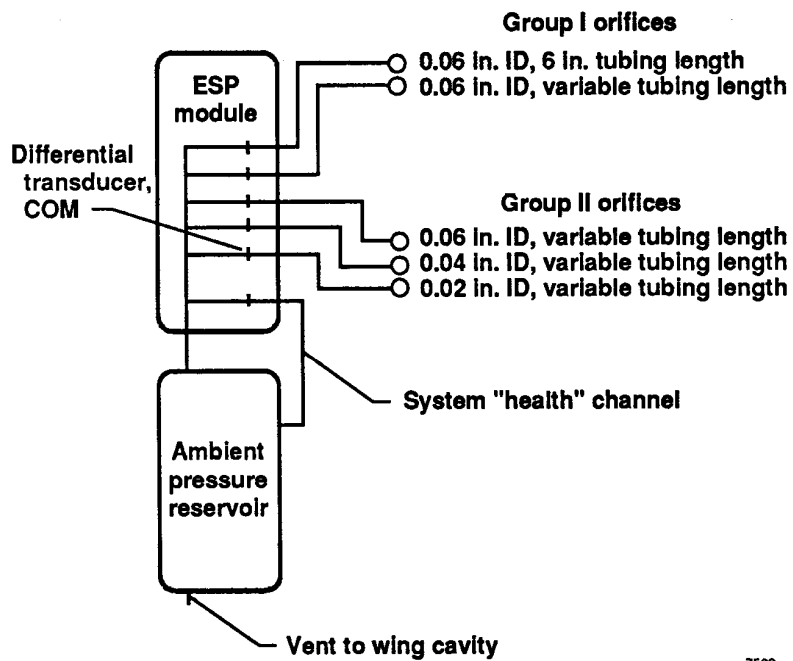| Nominal value, in.	Actual orifice diameter, in.	Actual tubing diameter, in.
0.02	0.023	0.020
0.04	0.045	0.040
0.06	0.061	0.060
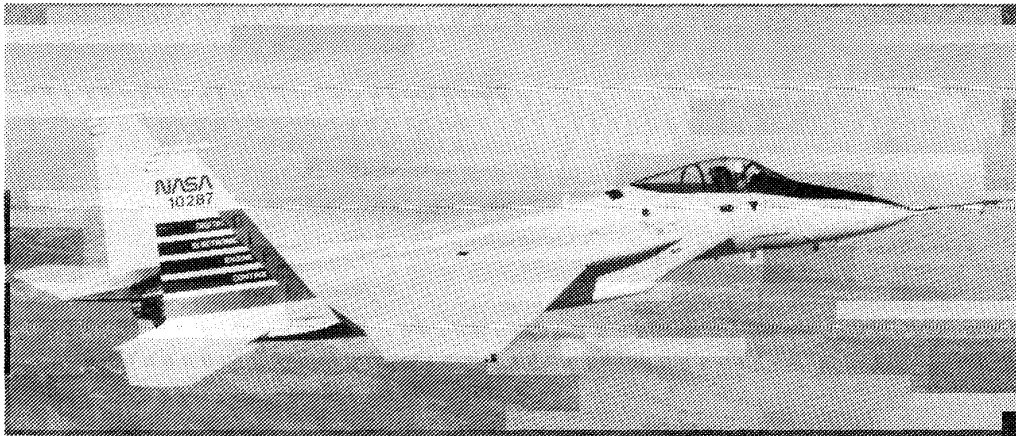
ECN 17710

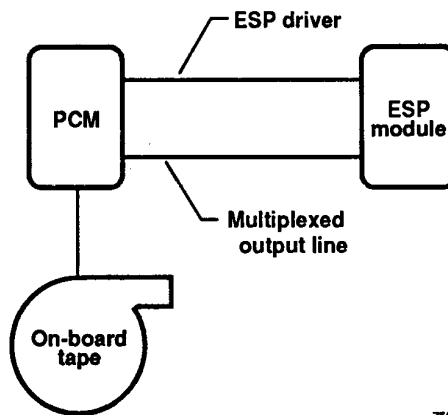(a) F-15 research airplane.

EC87 0194-003

(b) Experimental system installation.

Figure 1. Photographs of the flight test configuration.

7

(a) Pneumatic tubing configuration.

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(b) Data system schematic.

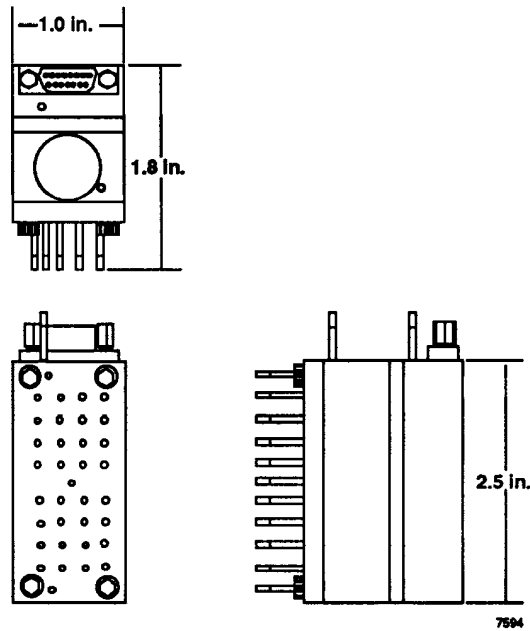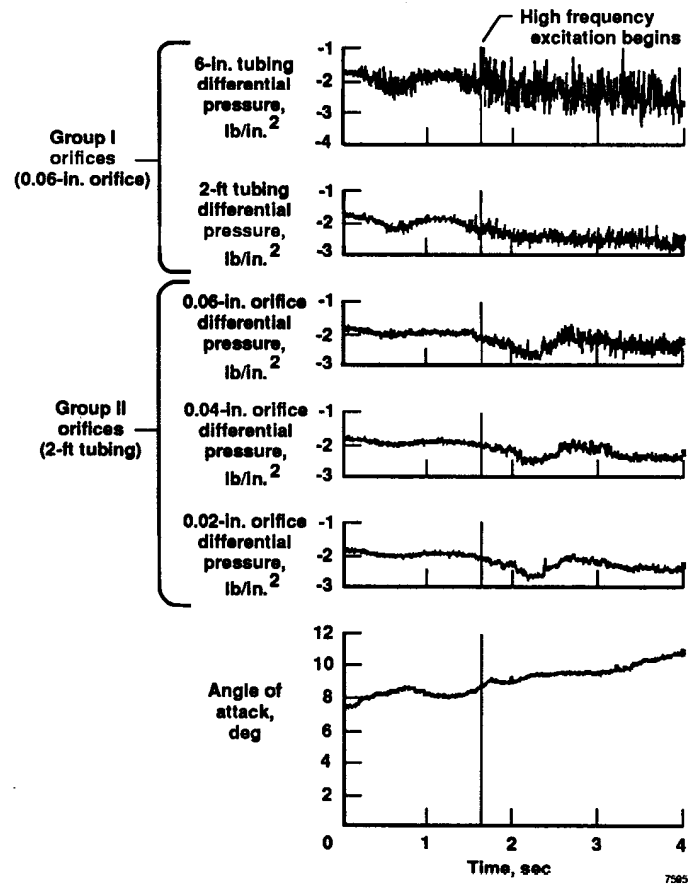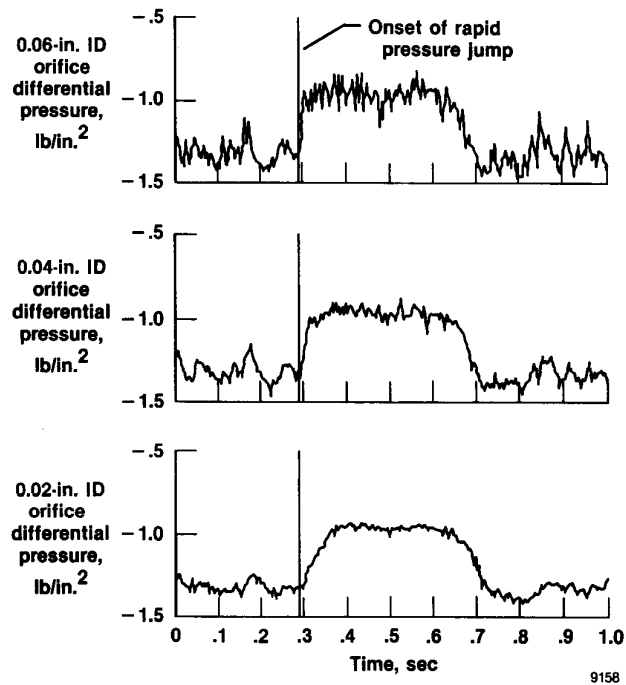Figure 2. Schematic of experimental pressure measurement system.
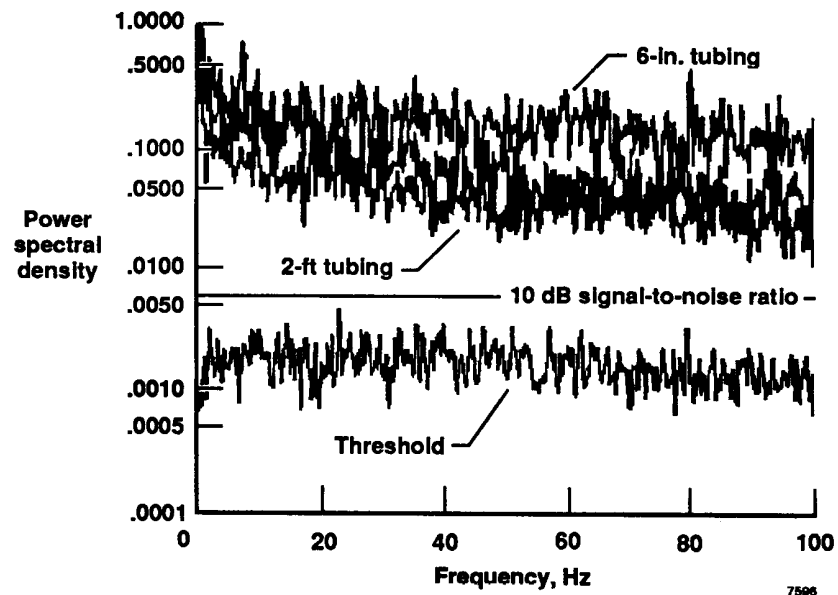
Figure 3. Electronic scanning pressure (ESP) module.

(a) Onset of high-frequency pressure fluctuations during a windup turn.
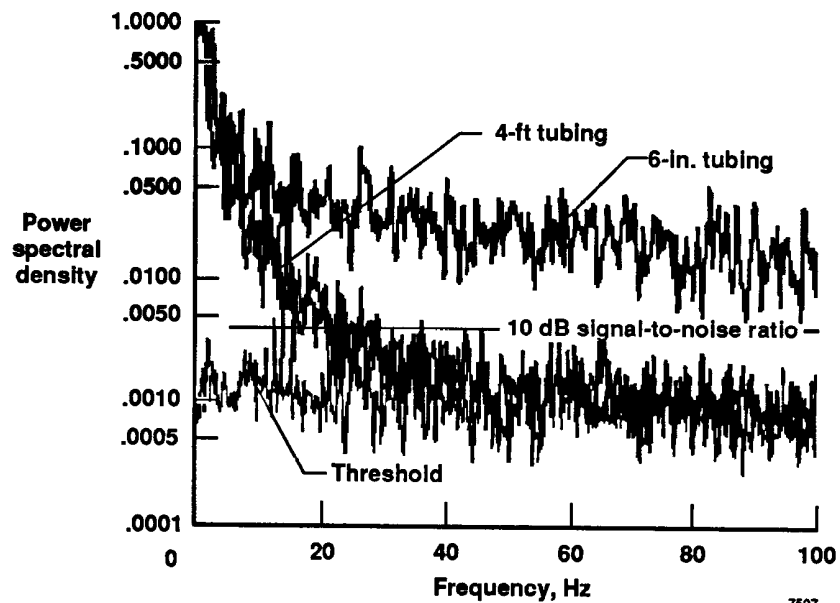
Figure 4. Examples of parameter time histories during maneuvering.

(b) Time history with rapid presure changes.

Figure 4. Concluded.

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10

(a) 2-ft tubing length, 20,000-ft altitude.

(b) 4-ft tubing length, 40,000 ft altitude.

Figure 5. Comparison of PSD levels for various tubing lengths, 0.06-in. orifice ID.
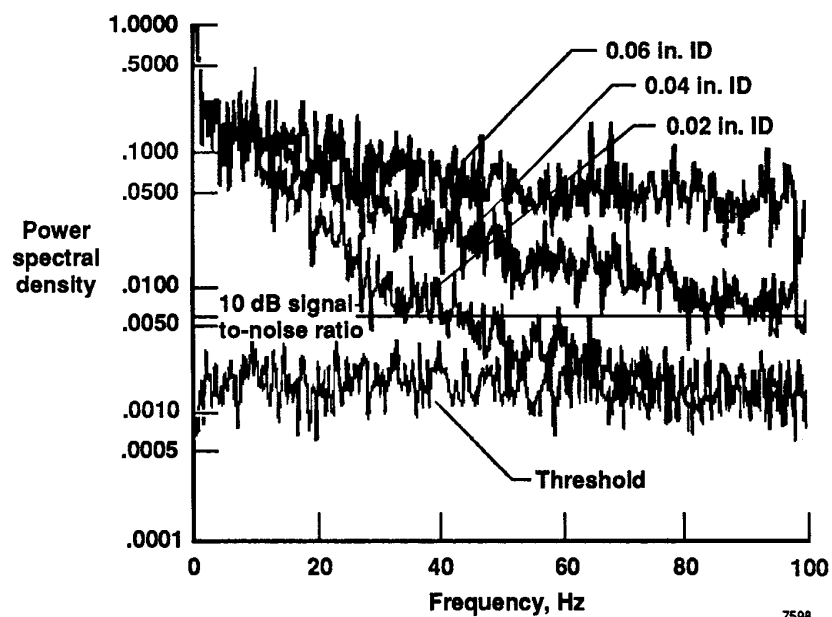
Figure 6. Comparison of PSD levels for various orifice diameters; 2-ft tubing length, 20,000-ft altitude.
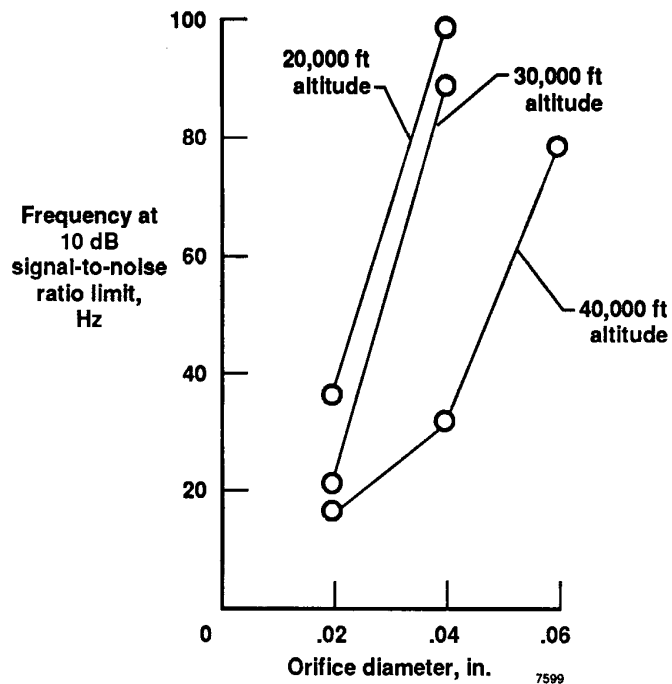
(a) 4-ft tubing length.

Figure 7. Signal-to-noise ratio limits of 10 dB observed from PSD analysis of flight data.
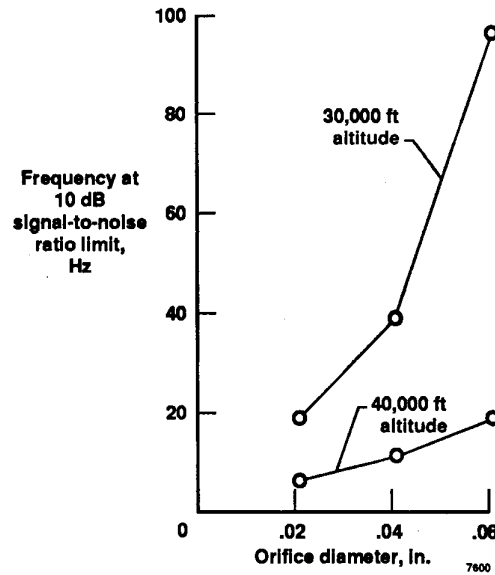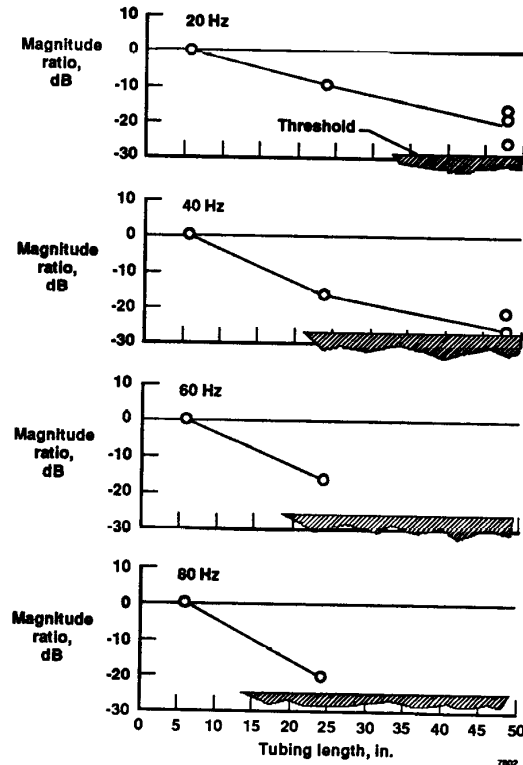
(b) 2-ft tubing length.
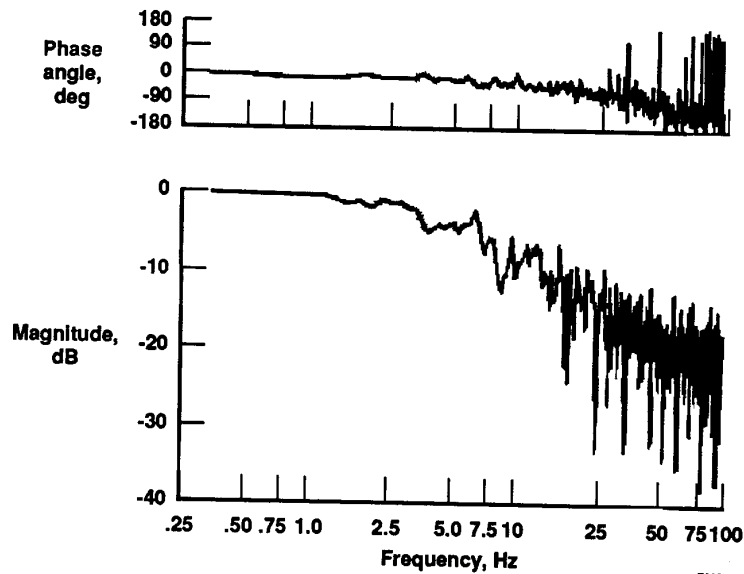
Figure 7. Concluded.
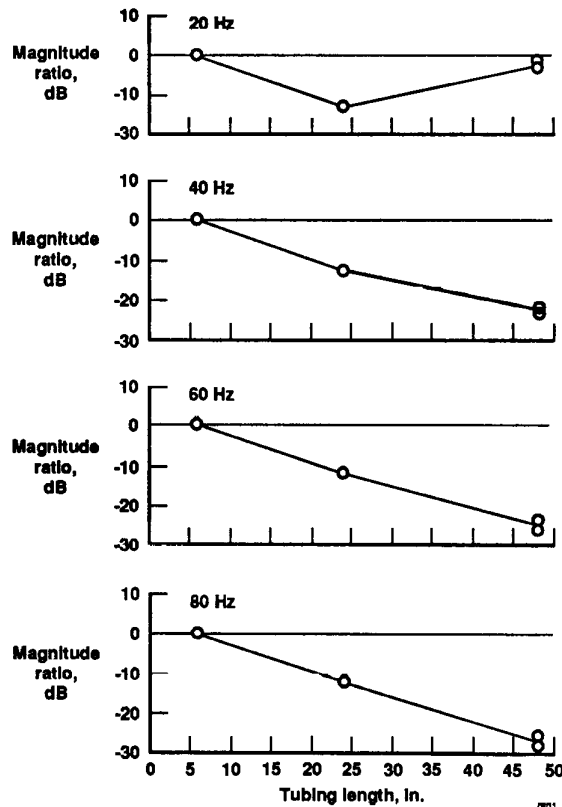
(a) 30,000-ft altitude.

Figure 8. Ratio of measured signal level to signal level of 6-in. tubing length signal for various frequencies. All data for 0.06-in. diameter orifices (group I).
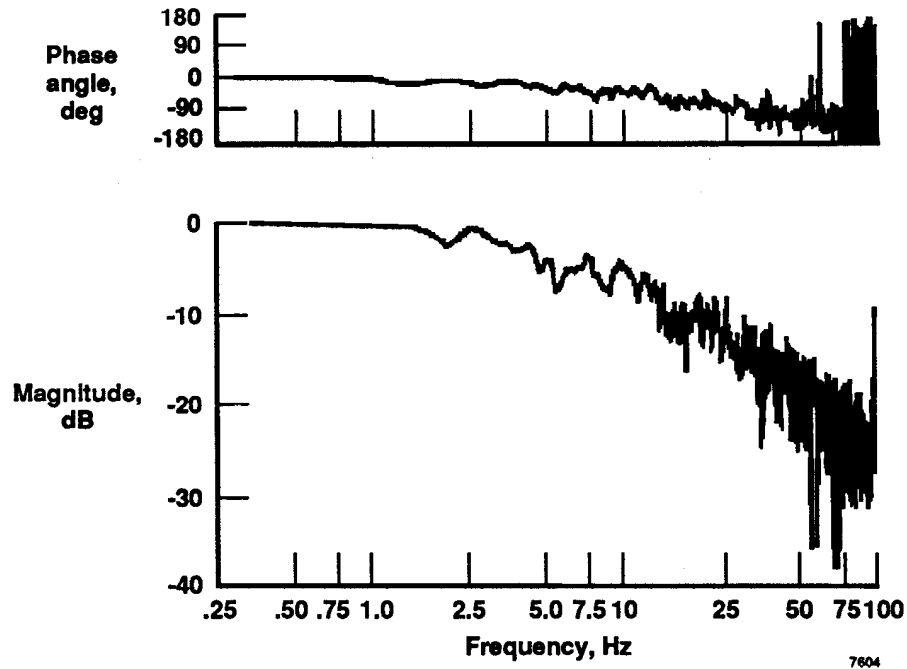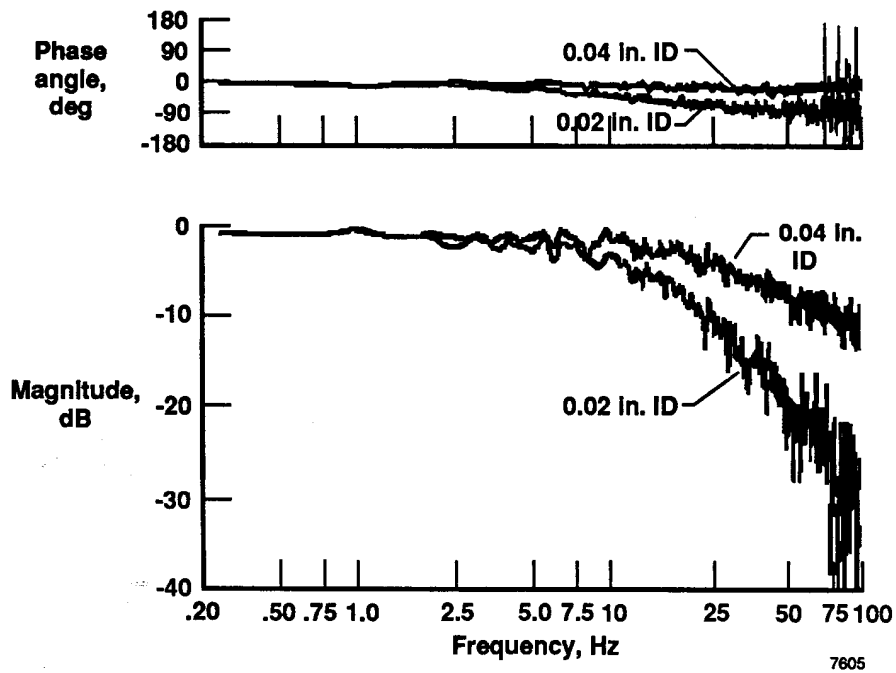
(b) 40,000-ft altitude.

Figure 8. Concluded.

(a) 2-ft tubing length, 40,000-ft altitude.

Figure 9. Transfer functions for various tubing lengths, referenced to the 6-in. tubing length configuration (all with 0.06-in. orifice diameter).
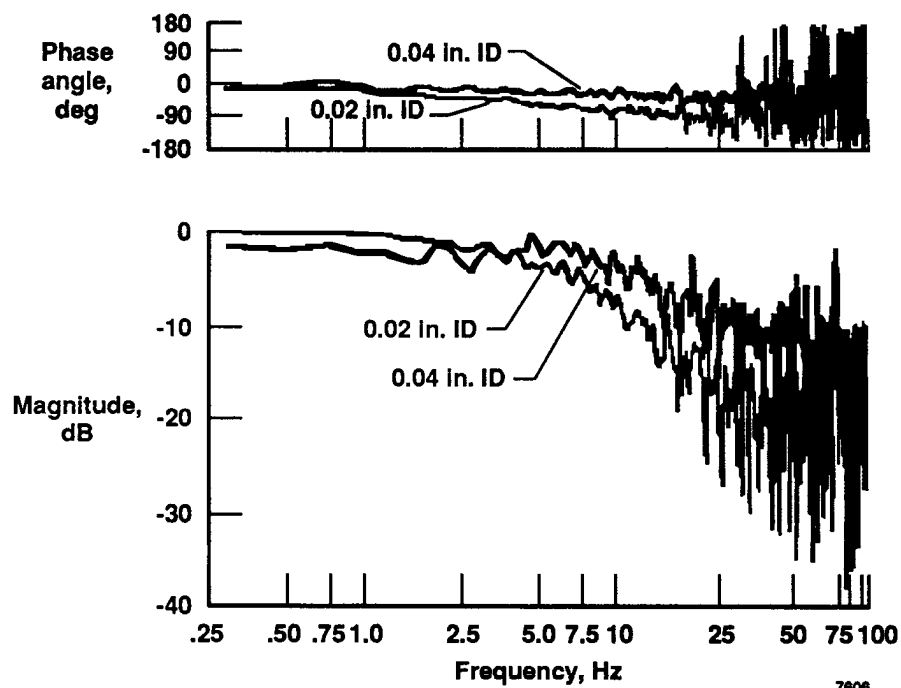
14

(b) 4-ft tubing length, 30,000-ft altitude.
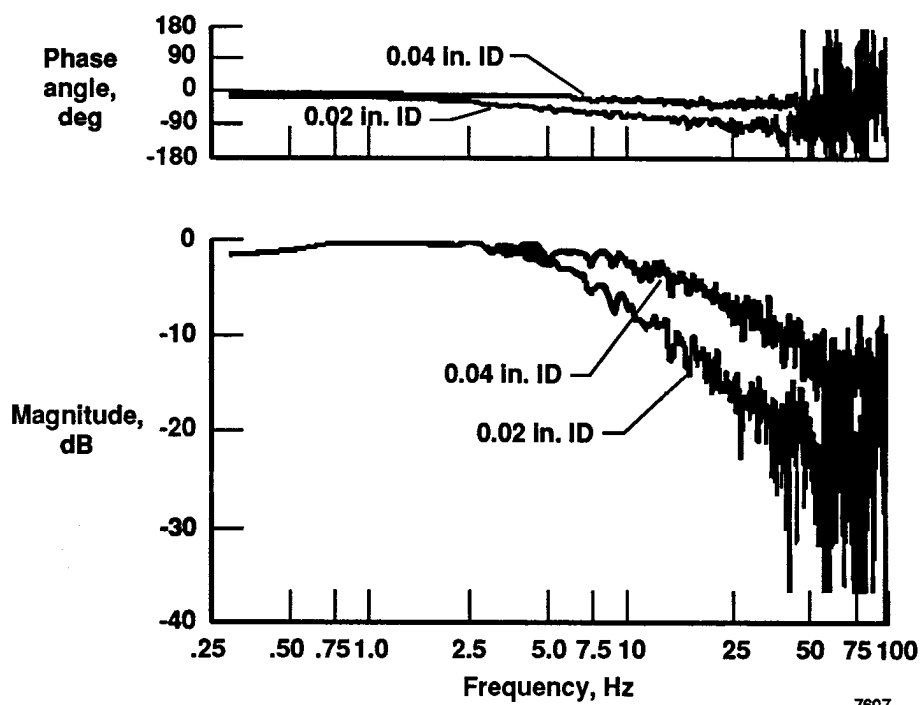
Figure 9. Concluded.

(a) 20,000-ft altitude.

Figure 10. Transfer functions for 0.02 and 0.04-in. ID orifices referenced to the 0.06-in. ID orifice for various altitudes, 2-ft tubing length.

15

(b) 30,000-ft altitude.

(c) 40,000-ft altitude.

Figure 10. Concluded.

16

Report Documentation Page

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15. Supplementary Notes

16. Abstract

A flight experiment was conducted to evaluate a pressure measurement system which uses pneumatic tubing and remotely located electronically scanned pressure transducer modules for in-flight unsteady aerodynamic studies. A parametric study of tubing length and diameter on the attenuation and lag of the measured signals was conducted. The hardware was found to operate satisfactorily at rates of up to 500 samples/sec per port in flight. The signal attenuation and lag due to tubing were shown to increase with tubing length, decrease with tubing diameter, and increase with altitude over the ranges tested. Measurable signal levels were obtained for even the longest tubing length tested, 4 ft, at frequencies up to 100 Hz. This instrumentation system approach provides a practical means of conducting detailed unsteady pressure surveys in flight.

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